USE OF SATELLITE DATA FOR MAPPING SNOW COVER IN THE WESTERN UNITED STATES

James C. Barnes, Clinton J. Bowley, and David A. Simmes
Environmental Research and Technology, Inc.
Lexington, Massachusetts 02173

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BIOGRAPHICAL SKETCH

James C. Barnes is Manager of Earth Resource Studies at Environmental Research and Technology, Inc. He received a B.A. in mathematics from Middlebury College and an M.S. in meteorology from New York University. He spent one year in Antarctica as meteorologist-in-charge of Ellsworth Station. During the past eight years Mr. Barnes has been involved in studies of meteorological and earth-resources applications of earth-satellite data. His main interest has been to develop techniques to use satellite data to map snow and ice. The studies for which he has been principal investigator have used photographic and radiometric data from meteorological satellites, including TIROS, ESSA, NOAA, and Nimbus, and from ERTS and Skylab.

ABSTRACT

The earth's snow cover is a water resource that directly or indirectly affects most of the world's population. In areas such as the western United States, where most of the utilized water comes from mountain snowpacks, accurate monitoring of snow is essential. Observation from earth satellites holds great promise for monitoring snow on a more cost-effective basis than can be accomplished by existing methods.

To evaluate the application of data from ERTS-1 for mapping snow, analyses have been performed for two test sites, the Salt-Verde Watershed in central Arizona and the southern Sierra Nevada in California. The results of the study indicate that snow extent can be mapped from ERTS imagery in more detail than is depicted on aerial survey snow charts. For the areas tested, the agreement between the percentage snow cover as determined from ERTS data and from aerial survey snow charts is of the order of 5 percent for most cases. Moreover, it appears that although small details in the snowline can be mapped better from higher-resolution aircraft photographs, boundaries of the areas of significant snow cover can be mapped as accurately from the ERTS imagery as from the aircraft photography. Moreover, the costs involved in deriving snow maps from ERTS imagery appear to be very reasonable in comparison with existing data collection methods.

INTRODUCTION

Snow has a momentous effect on the large-scale geophysical environment of the earth. Seasonal changes in snow cover produce variations in albedo that are unmatched by any other phenomena. The albedo variations have a significant influence on the radiation balance at the surface, which, in turn, influences both short-term and long-term weather conditions. Snow also plays a vital role in the overall world-wide water balance.

In the western United States snow has a direct economic impact. In many parts of the West a large part of the utilized water comes from accumulated mountain snowpacks. The snowmelt runoff is used for irrigation, industrial production, power generation, public consumption, and recreation. Too much runoff may have strong adverse effects in the form of distructive flooding. One only has to look at this past winter to gain an understanding of the impact of snow on the economy of the western part of the country; in central Arizona exceptional winter snowfall has resulted in replenished

groundwater and a summer of abundant water supplies, whereas in the Pacific Northwest a winter of well-below normal snowfall has produced a power-generation crises.

Despite the economic and scientific implications of snow cover, existing data collection methods often cannot provide either the desired areal coverage nor observational frequency. Except in limited areas where aerial survey is used, the significant parameters are usually measured at ground stations or at widely scattered snow survey courses. Now, the capabilities of remote sensing from earth-orbiting satellites offer promise for the development of a more cost-effective means for monitoring snow cover. Certainly, the satellite is the only economically feasible means to monitor snow on a world-wide basis.

APPLICATION OF ERTS DATA

In a report on the management of California's snow-zone lands for water, Anderson (1963) discusses two important characteristics of the Sierra Nevada snowpack: (a) maximum accumulation of snow, and (b) rate of melt of snow water from the pack. The first characteristic is a good indicator of total water yield, and the second of when the resulting water is delivered. Both of these characteristics may be related in some degree to the snow extent. In a study using aerial photographs, Leaf (1969) found that for each of three Colorado watersheds a functional characteristic exists between extent of snow cover during the melt season and accumulated runoff. He reports that snow-cover depletion relationships are useful for determining both the approximate timing and the magnitude of seasonal snowfall peaks.

Snow could be detected in the first TIROS photographs more than a decade ago. Since then considerable research has been carried out to determine snow survey and other hydrologic applications of environmental satellite data (McClain, 1970). Through studies performed by Barnes and Bowley (1970, 1972) techniques to map snow cover from existing photographic and thermal infrared measurements have been developed. These studies have shown that valuable information on snow extent can be derived from spacecraft observations.

Nevertheless, limitations in the use of satellite systems designed primarily for meteorological purposes do exist. Cloud interference, which limits the number of usable satellite observations, remains a problem (for hydrologic purposes, however, daily snow observation is not normally required). Also, since mountain regions are commonly forested, vegetation effects may also influence the location of the snow line in satellite photographs. Of greater significance is that the mapping accuracy that has been attainable from the relatively poor-resolution cameras is only marginal for optimum hydrologic use. Now, ERTS-1 is providing the first opportunity to investigate the application of high-resolution multispectral data for snow survey. Through use of these data, many of the previous problems can be alleviated.

This paper describes an investigation to evaluate the application of ERTS data for mapping snow cover in the mountainous areas of the western United States. The specific objectives of the study were to determine the spectral interval most suitable for snow detection, determine the accuracy with which snow lines can be mapped in comparison with the accuracies attainable from other types of measurements, and develop techniques to differentiate reliable between snow and clouds and to understand the effects of terrain and forest cover on snow detection. The snow extent mapped from the ERTS imagery has been correlated with standard snow measurements, aerial survey snow charts, and aerial photography. The study has been concentrated in two geographic areas, the southern Sierra Nevada in California and the Salt-Verde Watershed in central Arizona.

PROCEDURES FOR IDENTIFYING AND MAPPING SNOW

Examination of the ERTS data has shown that contrast between snow covered and snow free terrain is greatest in the MSS-4 (0.5 to 0.6 μm) and MSS-5 (0.6 to 0.7 μm) spectral bands. The MSS-5 data appear to be the more useful of the two bands for snow mapping, because in some of the MSS-4 images snow covered areas are near saturation, causing a loss of detail in the snow pattern. In the longer wavelengths, especially the MSS-7 near-IR band (0.8 to 1.1 μm), snow cover is more difficult to detect. However, the near-IR band, which has been found extremely useful for studies of glaciers and sea ice in the Arctic, may provide information for certain purposes such as detecting melting conditions. A limited sample of color composite data have also been examined. Although a thorough evaluation of the advantages of the color product must await additional data, the initial examination indicates that color may have some advantages for detecting and mapping snow.

Snow cover can be identified in the MSS-5 data because of its greater reflectance than the surrounding snow free terrain. Although snow and clouds have similar reflectances, mountain snow cover can be differentiated from cloud primarily because the configuration of the snow patterns is very different from cloud fields and can be instantly recognized. The snow boundaries are also sharper than typical cloud edges, and snow fields usually appear with a more uniform reflectance than do clouds, which have considerable variation in texture. Furthermore, cloud shadows are usually visible, especially with cumuliform clouds, and various terrestrial features can be recognized in cloud-free areas. Because of the high-resolution of the ERTS data, numerous terrestrial features that are not visible in lower-resolution meteorological satellite photographs can be recognized. In addition, to natural features, such man-made features as roads, power line swaths, and cultivated fields are detectable. In the heavily forested areas of the Cascades, timber cuts are clearly visible.

In the analysis procedure the snow line was mapped at the edge of the brighter tone without regard to changes in brightness within the overall area deduced to be snow covered. Although snow covered areas often exhibit fairly uniform reflectance, variations due primarily to forest effects are observed. For the specified test sites the snow limit was mapped from the 9.5 inch ERTS prints supplied by NASA (scale 1:1 million) and, in some instances, from reprocessed enlarged prints (scale 1:500,000). In the central Arizona test site no significant differences have been found between the original and reprocessed prints. In the Sierra Nevada test site, however, the effects of mountain shadows, which are a problem in the low-sun angle winter data, are reduced through the reprocessing; in some areas snow - no snow boundaries that are obscured in the original prints can be detected. Because the scale of the 9.5-inch ERTS prints is the same as the scale of aerial survey snow charts (1:1 million), used as one source of correlative information, transfer of the snow extent mapped from the ERTS image to the aerial survey base map could be easily accomplished.

ANALYSIS OF DATA FOR SALT-VERDE WATERSHED

The 1972-73 winter season produced a record snowpack accumulation in the Salt-Verde Watershed in central Arizona. Precipitation for the October through April period was much above normal, and the snowpack at its maximum in early April was estimated to be as much as 500 percent of normal in the Verde River Watershed and 300 percent in the Salt. In April the runoff forecast for the Verde was nearly 400 percent of the 1953-1967 average and for the Salt more than 350 percent. Obviously, throughout this past winter-spring season, snow hydrology was a vital concern in Arizona water management programs.

Snow extent for at least a portion of the Salt-Verde Watershed could be mapped from imagery for seven of the ten ERTS cycles between mid-November 1972 and early May 1973. For each cycle the eastern third of the watershed is covered on one day and the remaining part (with some overlap) on the following day. On one occasion (26 December) most of the area is cloud-free, but the imagery is not of useable quality. Thus, even in a year with much above average precipitation, the central Arizona area is sufficiently cloud-free that useful snow information can be derived on 80% of the ERTS cycles.

Aerial snow survey charts of the Salt-Verde Watershed were acquired from the Salt River Project Office for dates nearest the dates of the ERTS data. The aerial survey procedures are described in a paper by Warskow (1971). For each aerial survey flight, which is made at approximately two-week intervals, an ocular estimate is made of the snow depth using the logs left from timber operations in the mountain areas, ground and vegetation textural characteristics, and cultural features (such as fences, road cuts) as indicators of the snow depth. Both the areal outline of the snow pack and the observed depths are recorded on a map overlay. Maps showing the snow extent derived from ERTS data and as depicted on the aerial survey charts for two dates in February are shown in Figures 1 and 2.

Comparison between ERTS data and aerial survey snow charts

The comparative maps shown in Figures 1 and 2 indicate that more detail in the snow line can apparently be mapped from the ERTS data than can be mapped by the aerial observer. In general, however, the locations of the snow lines are in good agreement, particularly in the Verde Watershed west of about 111°W. In nearly all areas in which a discrepancy occurs, the aerial survey chart depicts a greater snow extent than is mapped from the ERTS imagery. In some cases this difference can be explained by melting that occurred during the interval between the observations; in a November case, for example, much of the light snow cover probably melted during the seven-day period between the two observations.

To obtain a quantitative evaluation of the differences between the ERTS data and aerial survey charts, the percentage of snow cover was computed. The total Salt-Verde Watershed was divided into three areas; the northwestern portion in which the agreement appeared to be the best, the central portion, and the eastern portion (the approximate areas are shown in Figure 2). The boundaries of the areas vary slightly from case to case because of variation in the exact area covered by ERTS and cloud conditions. The percentage of the area snow covered was then measured for each section using a compensating polar planimeter.

Overall, the mean difference in the percentage of the watershed snow covered is 8 percent. The mean difference for Area 1 is 6 percent and for both Areas 2 and 3, 10 percent. In every measurement taken, the percentage of the area snow covered mapped from ERTS is less than the percentage measured from the aerial survey snow chart. The greatest difference is 18 percent, measured in Area 2 in the November case and in Area 3 in the March case. In both cases a significant change in snow cover probably occurred between the time of the ERTS data and the aerial survey.

Comparison between ERTS imagery and aircraft photography

On 16 March aircraft data for the central Arizona mountains were collected by the NASA/ARC Earth Resources Aircraft Project. The high-altitude aircraft data consist of 70 mm black and white photography (plus X-2402 film in the 0.475-0.575 μm and 0.580-0.680 μm spectral bands, and infrared aerographic -2424 film in the 0.690-0.760 μm band), 70 mm color photography

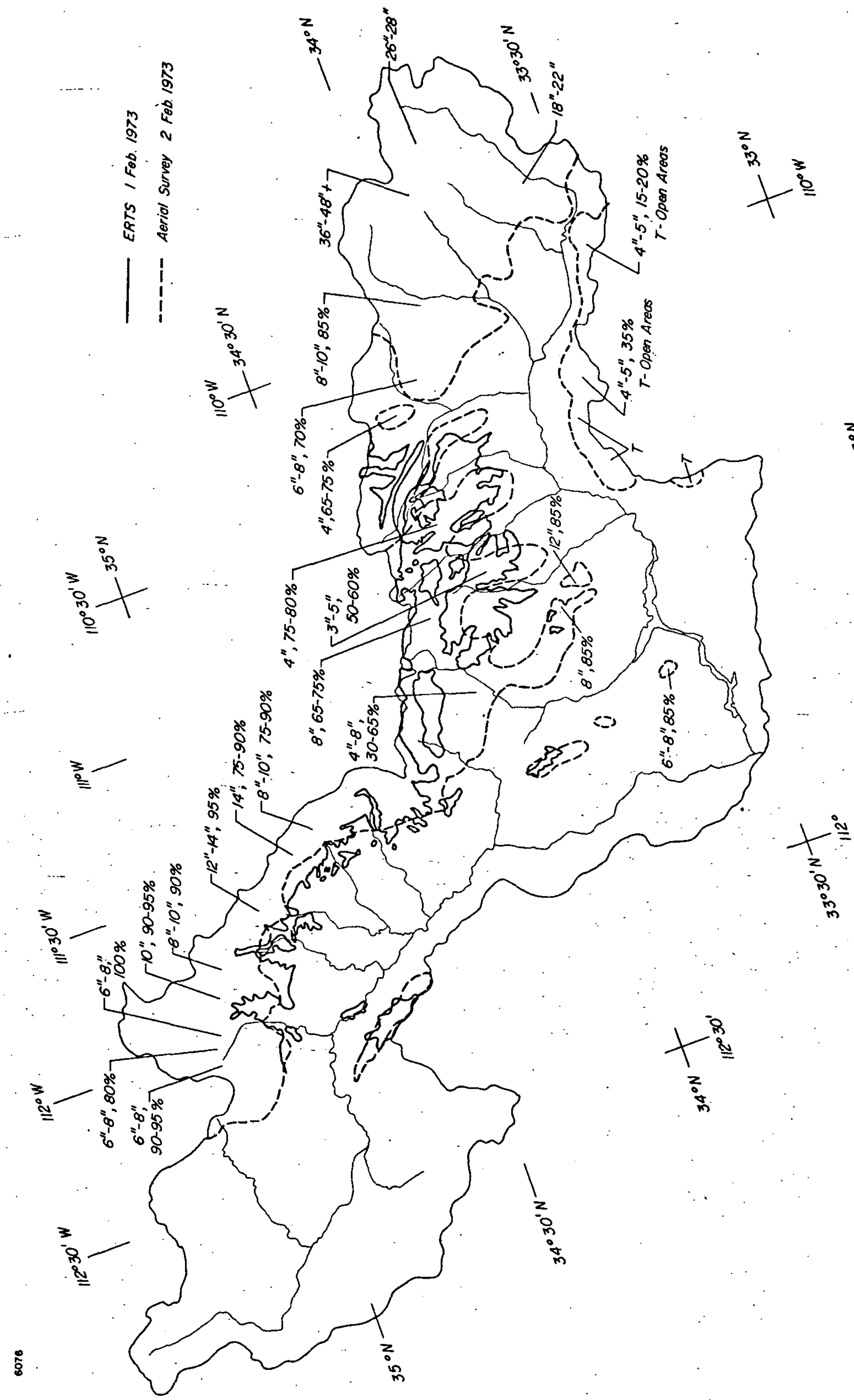

Figure 1 Comparison between snow line mapped from ERTS MSS-5 image (ID 1193-17330) and that depicted on aerial survey snow chart, Salt-Verde Watershed, Arizona, early February. Eastern part of watershed was not covered in the ERTS image.

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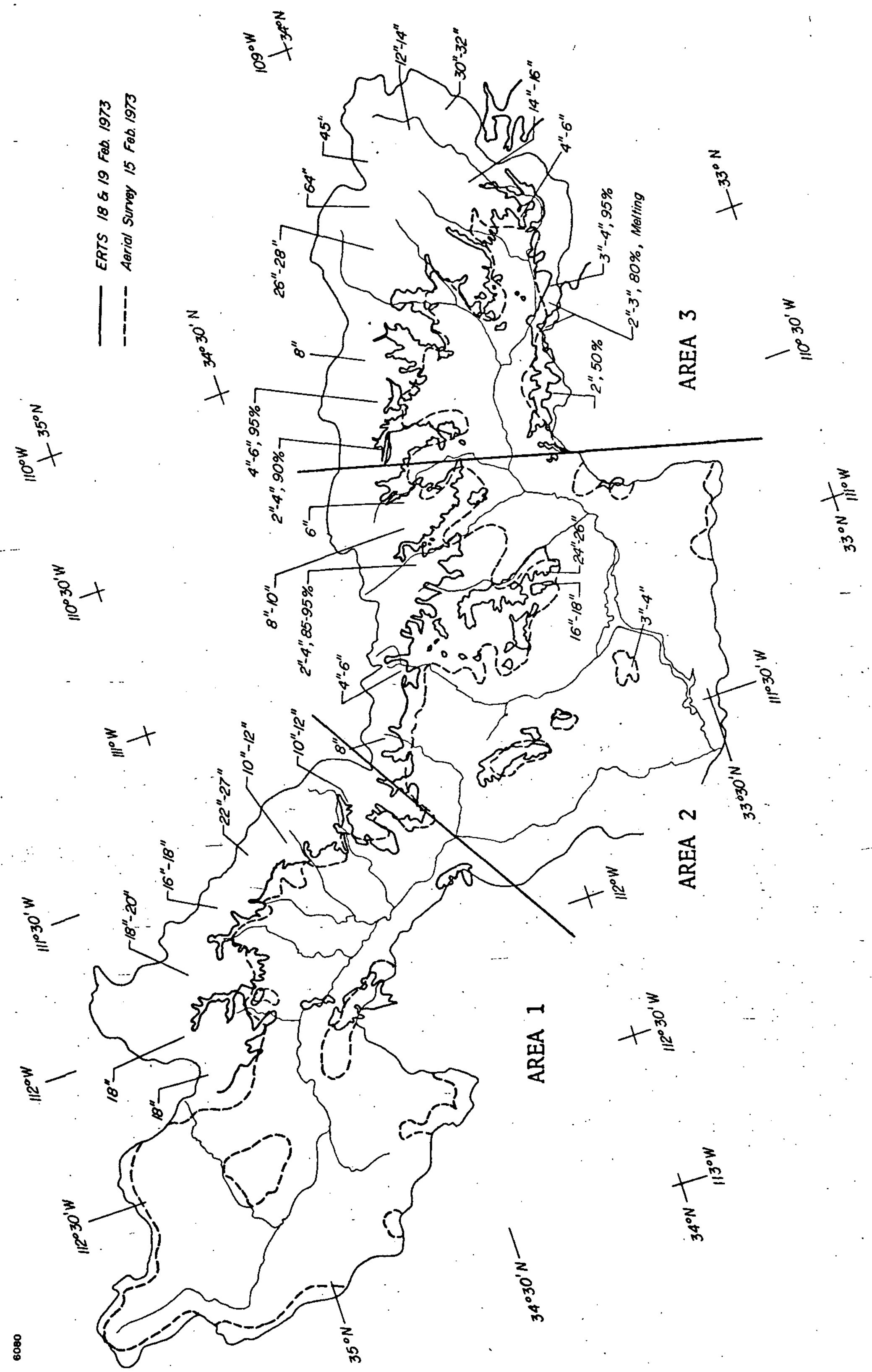

Figure 2 Comparison between snow line mapped from ERTS MSS-5 images (ID 1210-17273 and 1211-17332) and that depicted on aerial survey snow chart, Salt-Verde Watershed, Arizona, mid-February. The eastern part of the area was covered on 18 February and the western part a day later.

(aerochrome infrared -2443 film in the 0.510-0.900 μm spectral band), and 9-inch color photography (same film as above). The 70 mm photography is from a Vinten sensor with a 1.75-inch focal length, and the 9-inch photography is from an RC-10 sensor with 6-inch focal length. Two segments of the flight path are over the Salt-Verde Watershed, one crossing the Flagstaff area in the Verde Basin and the other crossing the Mt. Baldy area in the eastern Salt Basin.

The ERTS data nearest the time of the aircraft flight are for 26 March, ten days later. During the intervening period, substantial snowfall did occur (about 20 inches at Flagstaff and 13 inches at McNary); however, the snow on the ground at both stations was less on the 26th (25 and 4 inches, respectively) than on the 16th (30 and 18 inches, respectively). The most recent previous snowfalls at both stations were on 14 March, two days before the aircraft flight, and on 23 March, three days before the ERTS passage. The preliminary results of the comparative analysis of these data indicate that no significant difference in snow detection is apparent between the 0.580-0.680 μm and 0.690-0.760 μm aircraft data products. In comparison with ERTS data, detailed snow features that cannot be detected in the ERTS imagery can be seen in the aircraft photography. However, it appears that all significant snow cover (i.e., substantial snow cover, not small amounts such as might be found along small topographic features) can be detected in the ERTS imagery.

Multispectral data analysis

ERTS color composite positive transparencies for 21 November and 19 February have been examined. Although a thorough evaluation of the advantages of the color products must await additional data, examination of the initial transparencies indicates that the color product may have some advantages for snow detection and mapping. In the color transparencies, water features such as lakes, resevoirs, and rivers can be more readily identified, as can vegetation areas and the locations of the treeline. In forested areas, snow appears to be more discernible than it is in the single-band data products. Furthermore, snow can be more easily distinguished from highly-reflective snow free rock surfaces and can be mapped more easily in shadow areas in the color composite data.

ANALYSIS OF DATA FOR SOUTHERN SIERRA NEVADA

The snowpack in the southern Sierra Nevada was also above normal this past season. The California Department of Water Resources reports that early in the winter the snowpack that had accumulated by late December was depleted at lower elevations and reduced at higher elevations by warm storms during early January, but subsequent storms and colder weather brought the snowpack to above normal by the first of February. A relatively wet February raised the water content of the snowpack, and the continuation through March of cool, wet weather boosted the snow water content to greater amounts in most watersheds. On the first of April, the snow water content at mid-elevations of the Kern, Kaweah, Tule, and Kings River Basins was greater in percentage of normal than at the higher elevations. In fact, two snow courses in this area had water contents that exceeded the maximum water content ever recorded. Although precipitation was below normal during April, the snowpack water content was still well above normal in early May. Snow course measurements made about the first of May indicated a snowpack water content as high as 315 percent of average in the Tule River Basin. On this date the water-year streamflow for the San Joaquin drainage area was forecast to be 100 to 150 percent of avarage.

In the ERTS orbital configuration the Kern Basin is covered on one day and the Kings, Kaweah, and Tule (and part of the Kern) on the following day. Because of cloud obscuration, the entire four-basin area was not mapped in

each case; however, during the period from early December through late May, a major part of the area was sufficiently cloud free to be mapped on seven of the ten ERTS cycles. Aerial survey snow charts depicting the snow extent in the four-basin area were prepared by the Corps of Engineers on 27 April, 11 May, and 22 May. Aircraft data were also collected over parts of the southern Sierras in support of the ERTS project by NASA/ARC on 20 February. Snow cover measurements from the California Cooperative Snow Survey Program are available for the first of each month, from February to May.

For each river basin of the southern Sierra Nevada the snow line elevation was determined directly by comparing the snow map derived from the ERTS image with superimposed elevation contours. In addition, the snow line elevation was determined by measuring the percentage of the basin snow covered and referring to the area - altitude curve for the particular basin. In an earlier study using meteorological satellite photography, the snow line elevation for the Kings Basin was determined in this way (Barnes and Bowley, 1970). Recently, the snow line determined from areal snow extent, or the equivalent snow line altitude (ESA), has been discussed further with regard to ERTS data (Meier, 1973).

The snow line elevation determined from a direct comparison with a contour chart varies considerable within each river basin. The Kings River Basin in the southern Sierras, for example, was divided into three sections, and the mean elevation for each section was determined from a large number of data points. For three cases during the spring season, the mean difference between the section with the highest snow line elevation and that with the lowest is 1400 feet. Because of the observed variation in the snow line elevation measured directly, which can be influenced significantly by small mapping errors, it is believed that the equivalent snow line altitude (ESA) is a more meaningful measurement with regard to the application of satellite data to snow mapping.

Comparison between ERTS data and aerial survey snow charts

The snow extent mapped from ERTS data is compared with the snow extent depicted on aerial survey charts for the three spring cases in Table 1. Because of cloud cover, the Kern Basin was not mapped. The results show that in every case except one the difference in percentage snow cover is less than 10 percent. The mean difference for the Kings Basin for the three cases in 5 percent, for the Kaweah 12.5 percent, and for the Tule 5.5 percent. The mean differences in the equivalent snow line altitude are 533, 1200, and 700 feet., respectively. For each case analyzed, the percentage snow cover determined from ERTS data is greater than that of the aerial survey chart; thus, the ESA determined from ERTS is lower than the ESA shown in the aerial survey chart.

As was pointed out in the discussion of the Arizona data, it appears that considerably more detail in the snow line can be mapped from ERTS imagery than is mapped by the aerial observer. The greatest discrepancy between the ERTS and aerial survey data occurs in late May in the Kaweah Basin, when the percentage snow cover is 18 percent greater for ERTS. A careful check of the geographic gridding of the image does not indicate an error that could account for the observed difference. A review of the image shows that certain areas, which are not depicted as being snow covered on the aerial survey chart, appear to be definitely snow covered. Weather charts indicate that snow could have fallen during the interval between the observations, but this cannot be ascertained for certain until climatological data for May can be acquired. This case is being reexamined in an attempt to resolve the apparent discrepancy.

TABLE 1

COMPARISON BETWEEN ERTS DATA AND AERIAL SURVEY SNOW CHARTS FOR RIVER BASINS OF SOUTHERN SIERRA NEVADA

River Basin	ERTS Date 1973	ERTS %	ERTS ESA	Aerial Survey Date 1973	Aerial Survey %	Aerial Survey ESA	Difference (Aerial Survey-ERTS) %	Difference (Aerial Survey-ERTS) ESA
Kings	20 Apr.	75	5700	27 Apr.	69	6500	6	800
	8 May	64	7000	11 May	59	7500	5	500
	26 May	56	7800	22 May	52	8100	4	300
	MEAN	--	--	--	--	--	5	533
Kaweah	8 May	45	6000	11 May	38	6600	7	600
	26 May	38	6600	22 May	20	8400	18	1800
	MEAN	--	--	--	--	--	12.5	1200
Tule	8 May	16	6400	11 May	11	7000	5	600
	26 May	13	6600	22 May	7	7400	6	800
	MEAN	--	--	--	--	--	5.5	700

% = Percentage of Basin Snow-Covered

ESA = Equivalent Snowline Altitude (in feet)

Comparison between ERTS imagery and aircraft photography

Similar aircraft data as were collected over the central Arizona mountains were collected by the NASA/ARC Earth Research Aircraft Project (ERAP) over the southern Sierra Nevada on 20 February. Three segments of the flight cross areas covered in the ERTS imagery of 25 February. Parts of two of the segments are within the four-basin area, whereas the third is just northeast of that area. The segment northeast of the Kings River Basin crosses Mono Lake and the Owens River in the vicinity of Bishop. In both the aircraft and ERTS data, the snow line can be identified in the area north of Bishop indicated on the topographic chart to be an area of volcanic tableland essentially unvegetated. The snow line appears to be at about the 5000 feet level, with little change having occurred during the five-day interval between 20 and 25 February. More detail in the snow line and same patchy snow south of the edge of the solid snow cover can be mapped from the aircraft data. However, the edge of the area of significant snow cover can be mapped as precisely from ERTS as from the aircraft photography.

In another segment of the overflight, the area of the Courtright and Wishon Reservoirs in the northern Kings Basin can be identified in both the ERTS and aircraft data. The two reservoirs, which are frozen and snow covered, and the Lost Peak area in between appear very bright. The surrounding area consists of a mixture of open and forested terrain, appearing alternately bright and very dark in the aircraft photography. In the ERTS image, the larger bright areas can be identified whereas the smaller areas are integrated with the forested areas to produce a gray tone. It appears, therefore, that even though more detailed patterns can be identified in the aircraft data, the information content of the ERTS image with regard to mapping snow cover is equal to that of the higher resolution photography.

CONCLUSIONS

Based on the results of the completed data analyses, it is concluded that the amount of information in ERTS imagery with practical application to snow mapping is substantial. Moreover, for two mountain areas in which snow hydrology is a major concern, the Salt-Verde Watershed in Arizona and the southern Sierra Nevada in California, useful snow cover information could be derived from ERTS data on 70 to 80 percent of the cycles during the past winter and spring seasons. Thus, in these two areas, cloud obscuration does not appear to be a serious deterrent to the use of satellite data for snow survey.

The results of the analysis of ERTS imagery for the Arizona and California test sites indicate that the extent of the mountain snowpacks can be mapped from ERTS data in more detail than is depicted in aerial survey snow charts. In the Salt-Verde Watershed, the agreement between the percentage of the area snow covered as measured from the ERTS data and from aerial survey charts is generally well within 10 percent. In nearly all of the areas in which greater discrepancies occur, the differences can be explained by changes in snow cover during the interval between the two observations. In the southern Sierra Nevada, the agreement between ERTS data and aerial survey charts is of the order of 5 percent in all cases, except for the Kaweah Basin on one date.

In addition to comparative analysis with aerial snow charts, the ERTS data have also been compared with high-altitude aircraft photography provided by the NASA/ARC Earth Resources Aircraft Project (ERAP). The results of the comparative analysis indicate that although small details in the snow line that cannot be detected in the ERTS data can be mapped from the higher-resolution aircraft data, the boundaries of the areas of significant snow cover can be mapped as accurately from the ERTS imagery as from the aircraft photography.

The costs involved in deriving snow extent maps from ERTS imagery appear to be very reasonable in comparison with current data collection methods. For example, the flight time to survey the Salt-Verde Watershed is approximately five hours, with another hour or so needed to compile the snow chart. On the other hand, the snow extent can be mapped from an ERTS image covering nearly the entire Watershed area by an experienced analyst in about two hours. Eventual machine processing can be expected to reduce this time considerably.

The major drawbacks to the use of ERTS data as imput to an operational system are the availability of the data and the rate of repetitive coverage. To be useful operationally the data would have to be made available to the user within twenty-four hours. The rate of repetitive coverage in the central Arizona area, where snowmelt can occur rapidly, would ideally have to be of the order of one week or less. In the southern Sierras, aerial surveys are normally conducted bi-weekly; thus, in that area a repetitive rate of coverage of the order of one week appears to be sufficient, allowing for the possibility of some data being cloud obscured.

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